PRELIMINARY STUDIES OF THE MECHANICAL BEHAVIOR OF HIGH-STRENGTH STAINLESS STEEL PRESTRESSING STRANDS

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ABSTRACT

This paper presents the preliminary results of a study examining the production, stress vs. strain behavior, and stress relaxation of corrosion-resistant 2205 and 2304 duplex stainless steel prestressing strands. These two duplex stainless steels were selected to produce ½" diameter 7-wire strand for further mechanical testing. Wires were cold drawn through 7 dies to a final diameter of 0.165-in. with an 80% reduction of cross-sectional area, then stranded and subjected to a low relaxation heat treatment. In addition to samples from the rod coils, wire samples were taken after passing through dies 3, 5, and 7 (0.25-in, 0.207-in, 0.173-in diameters, respectively), and stress-strain plots were generated for each of these specimens in order to track mechanical behavior with reduction of area. Ultimate tensile strengths of 242 and 260 ksi were measured for 2205 and 2304 strands, respectively. Ultimate strain typically ranged from 1.5 to 2.0 % for both types of strand. Stress relaxation of 2205 strand was measured to be approximately 2.5% over 1000 hours when subjected to 70% UTS. Due to high notch sensitivity, stress relaxation testing of the 2304 strand was conducted at 40% UTS, and relaxation was found to be 2.1% over 1000 hours.

Keywords: Stainless Steel, Creative/Innovative Solutions and Structures; Piles, Prestressed; and Research

INTRODUCTION

Bridges and other coastal structures in Georgia and throughout the Southeast are deteriorating prematurely due to corrosion[1,2]. Numerous corrosion initiated failures have occurred in precast prestressed concrete (PSC) piles and reinforced concrete (RC) pile caps, leading to the costly repair and replacement of either the entire bridge or the affected members[1]. Figure 1 shows the results of a study of Georgia Department of Transportation (GDOT) bridge inspection records for bridges with concrete pile substructures along Georgia's coastal counties. Approximately 30 %, or 85 out of 290, of the bridges showed substructure ratings of 6 or less (shown by red dots in Figure 1), indicating that piles exhibited visible damage. Reported damage included cracking, rust staining, spalling, biological growth, and physical abrasion. While other examples of reinforcement corrosion can be found elsewhere, it is believed that numerous corrosion-related failures go undocumented and are settled through litigation before any investigation or research is conducted[3].

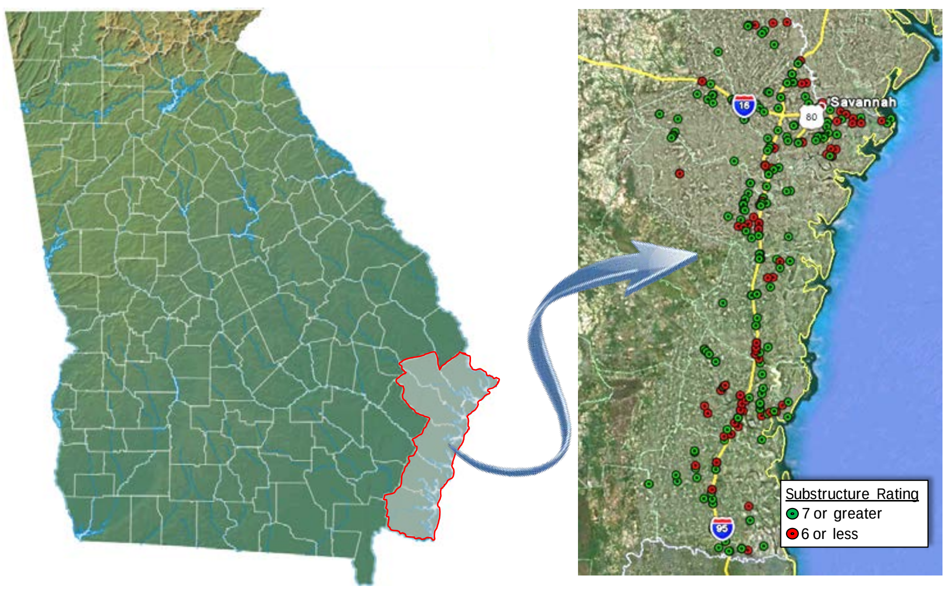


Fig. 1 Bridge Substructure Deterioration in Georgia's Coastal Counties

With the Federal Highway Administration's goal of a 100-year bridge service life and recent legislative action such as the Bridge Life Extension Act, new emphasis has been placed on the development and implementation of new corrosion mitigation techniques[4,5]. Traditional methods of corrosion mitigation in PSC structures include the use of lower permeability high-performance concrete, larger cover thicknesses, and proper design and construction to limit cracking. However, each of these methods only reduce amount of time needed to reach a sufficient chloride concentration at the surface of the steel to initiate pitting corrosion. In order to raise this threshold, corrosion resistant prestressing steel is being investigated. Moser conducted a preliminary investigation into high strength stainless steel (HSSS) alloys were found to be viable options for the production of strand samples for further investigation[6]. Cold drawn wires were created from six different stainless steels, including austenitic, duplex (austenite and ferrite), and martensitic alloys. The wires were evaluated based on their strength, corrosion resistance, stress relaxation behavior, cost, and availability. While each alloy exhibited sufficient tensile strength and similar relaxation, duplex grades 2205 and 2304 were proven the most corrosion resistance in seawater, chloride rich environments, and they were selected for production of ½" 7-wire prestressing strand conforming to ASTM A416[7].

In this report, the production of 2205 and 2304 HSSS prestressing strand is detailed and its mechanical properties and stress relaxation behavior are examined in order to compare with prestressing strand currently used in practice. The feasibility of the implementation of HSSS prestressing strand into PSC structures is also discussed. Additional tests were performed on drawn wire specimens extracted at varying points in strand production to demonstrate the influence of cold drawing and low relaxation treatment on the mechanical properties of the HSSS wire.

MATERIALS

ALLOYS SELECTED FOR STRAND PRODUCTION

Duplex grades 2205 and 2304 were chosen for strand production based on their low corrosion susceptibility. While 2205 was shown to be more resistant to corrosion, 2304, a "lean duplex" stainless steel, was also selected as a lower cost option due to its lower Mo and Ni contents. It is estimated that the cost of these HSSS strands is 6 to 8 times the cost of ordinary strand. The composition and pitting resistance equivalency number (PREN) of these steels and standard of practice high carbon 1080 prestressing steel is shown in Table 1. PREN is calculated by an empirical equation that is based on the compositions of Chromium, Molybdenum and Nitrogen; pitting resistance increases with the addition of each.

Table 1: Composition of Alloys Selected for Strand Production

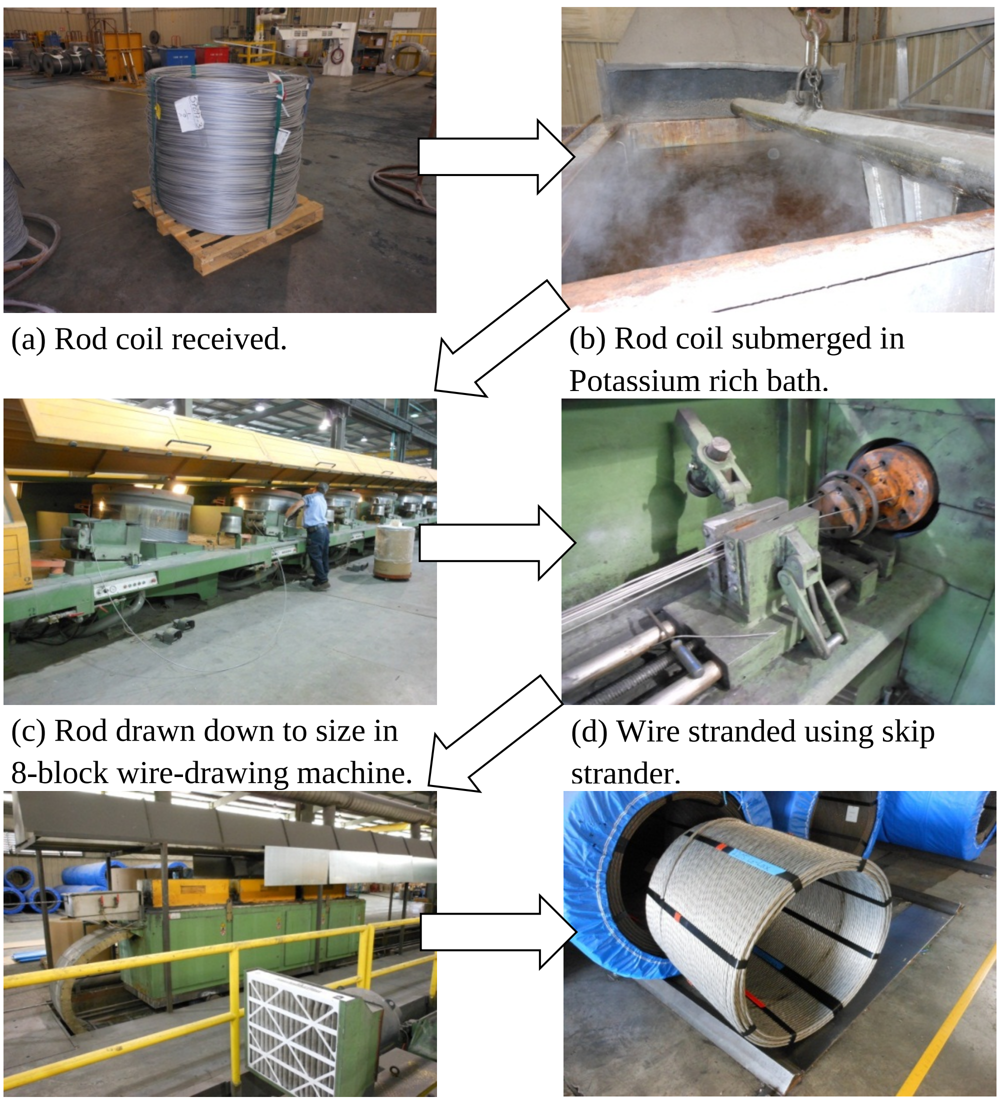
Alloy	Structure	Composition (%) – Balance Fe				PREN
		Cr	Ni	Mo	Other	
1080	Pearlitic	-	-	-	0.8C	<0.1*
2205	Duplex	22	5.5	3	0.17N	37.0
2304	Duplex	23	4.8	0.3	0.10N	27.0

*Contains trace Cr, Mo, N.

STRAND PRODUCTION

Stainless steel strand was produced from the two candidate HSSS using equipment typically used in the production of high carbon prestressing strand. Rod coils were dipped in a potassium salt solution for cleaning prior to cold drawing that was performed at a rate of 9.8 ft/s. The wires were drawn through seven dies, sequentially reducing the area of the wire down to sizes corresponding to ASTM ½" A416 prestressing strand and an 80 % reduction of cross-sectional area. Samples were taken from dies #3, #5, and #7 (0.25-in, 0.207-in, 0.173-in diameters, respectively) as well as the rod coil (0.375-in diameter) for the purpose of monitoring mechanical properties as the wire is drawn.

Seven wire prestressing strand was produced from the drawn wire using a skip strander. Both varieties of strand were then subjected to a low relaxation thermomechanical treatment using an induction furnace. The induction heating efficiency of the stainless steels was initially assumed to be lower than that of 1080 steel, and the induction heater was set to lower efficiency and adjusted to meet the desired temperature while monitored by infrared camera and rolling thermocouple. The 2205 strand was subjected to 380^0 C and a pull force of 40 % of the ultimate tensile strength (UTS) of the cold drawn wires. The first length of 2304 strand was subjected to the same treatment as 2205. A second length was treated with 380^0 C and a pull force of 45 % UTS of the first length of treated strand. 2304 strand results in this study correspond to the second length. An overview of the strand production is shown in Figure 2.



(a) Rod coil received.

(b) Rod coil submerged in Potassium rich bath.

(c) Rod drawn down to size in 8-block wire-drawing machine.

(d) Wire stranded using skip strander.

(e) Strand subjected to low relaxation treatment in furnace.

(f) Treated strand coiled and packaged.

Fig. 2: Production of HSSS Strand

METHODS

MECHANICAL TESTING

Stress vs. strain behaviors were evaluated for strand and wire samples by direct tension in a universal testing machine in accordance with ASTM A370[8]. A 30-in length between grips and 150 lb/s load rate in the elastic range (strain rate of approximately 0.0025 in/in/min) was used for strand tension testing. The strain rate was maintained after yield, and the load rate decreased. Strain was measured using a 24-in extensometer for loads under 80 % UTS and until failure using the relative position data of the machine heads, measured by string potentiometer. The extensometer was removed prior to failure to avoid damage, but the strain calculated from position data was matched with the extensometer data to provide a full, smooth stress vs. strain curve.

A gage length of approximately 8-in and a displacement rate of 0.1 in/min (strain rate of 0.0125 in/in/min) were used for all direct tension tests on single wires. A 2-in extensometer was used and removed at 90 % UTS and position data generated from the testing machine was used to calculate the remainder of the strain data.

STRESS RELAXATION TESTING

Stress relaxation testing on strand specimens was performed in a temperature controlled room in accordance with ASTM E 328[9]. 10-ft long steel HSS sections were used as a frame to provide constant strain to the stressed strand inside, as illustrated in Figure 3. At the dead end of the frame, a hollow core steel vibrating wire load cell was placed around the strand and anchored at the end with a chuck. At the jacked end, the strand was run through a hollowed bolt and nut, and a chuck was placed at the face of the bolt prior to loading. A steel housing was then set at the face of the frame and a U-washer, jack, load cell and chuck were placed on the strand. The U-washer allowed for easier removal while the load cell was used to monitor load during jacking. After the strand was jacked to its desired load, the bolt was turned until tight with the chuck inside the housing. Load was then taken off the jack and initial load was confirmed by the vibrating wire load cell at the opposite end.

For 2205 strand, triplicate tests were conducted at 70 % UTS for a 1000 hr term as well as single tests loaded to 50 % and 80 % UTS for 200 hr each. The shorter term tests were extrapolated to provide 1000 hr relaxation values. Due to notch sensitivity of the 2304 material, the 2304 strand could not be stressed to the same levels. Instead, three 1000 hr tests at 40 % UTS were performed. ASTM A416 requires no more than 2.5 % loss due to stress relaxation over 1000 hr for low relaxation steels when initially stressed to 70 % UTS and 3.5 % when stressed to 80 % UTS.

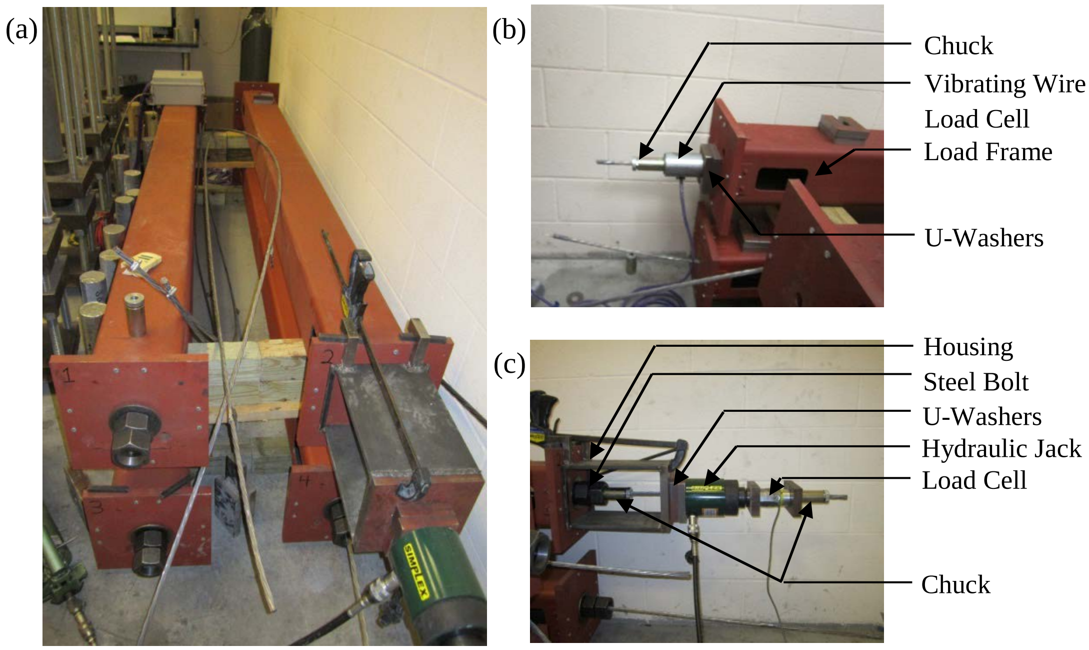


Fig. 3: a) Relaxation Frame, b) Dead End of Frame, c) Jacked End of Frame During Loading

RESULTS

STRESS STRAIN BEHAVIOR OF HSSS STRAND

Figure 4 gives stress-strain relations for strands composed of 2205, 2304 and 1080 steels, and Table 2 shows the corresponding mechanical properties. While the HSSS strands exhibited less tensile capacity than 1080 strand, their ultimate strengths are within 8 to 15 % of the 1080 strand, meaning that approximately 8 to 15 % more strand would be necessary to construct a similar structure to one made with 1080 strand. The main concern for design with these HSSS strands is their low ductility—approximately 30 % that of 1080 strand. Strain localization immediately followed yielding, as seen in preliminary tests of drawn HSSS wires, and failure was categorized by necking of the wires. Further studies are required to investigate methods of improving the ductility and inducing strain hardening in the drawn HSSS strand.

The yield strength of 1080 prestressing strand is often determined to be the stress corresponding to 1 % strain on the stress vs. strain diagram; this 1 % strain typically provides approximately the same value of the yield strength calculated by the 0.2 % offset method. However, due to a decrease in Young's modulus in the HSSS strand, the yield point calculated by the 0.2 % offset method was seen to be near 1.2 % strain, and the 1 % strain method underestimated the yield strength by 5 to 8 %.

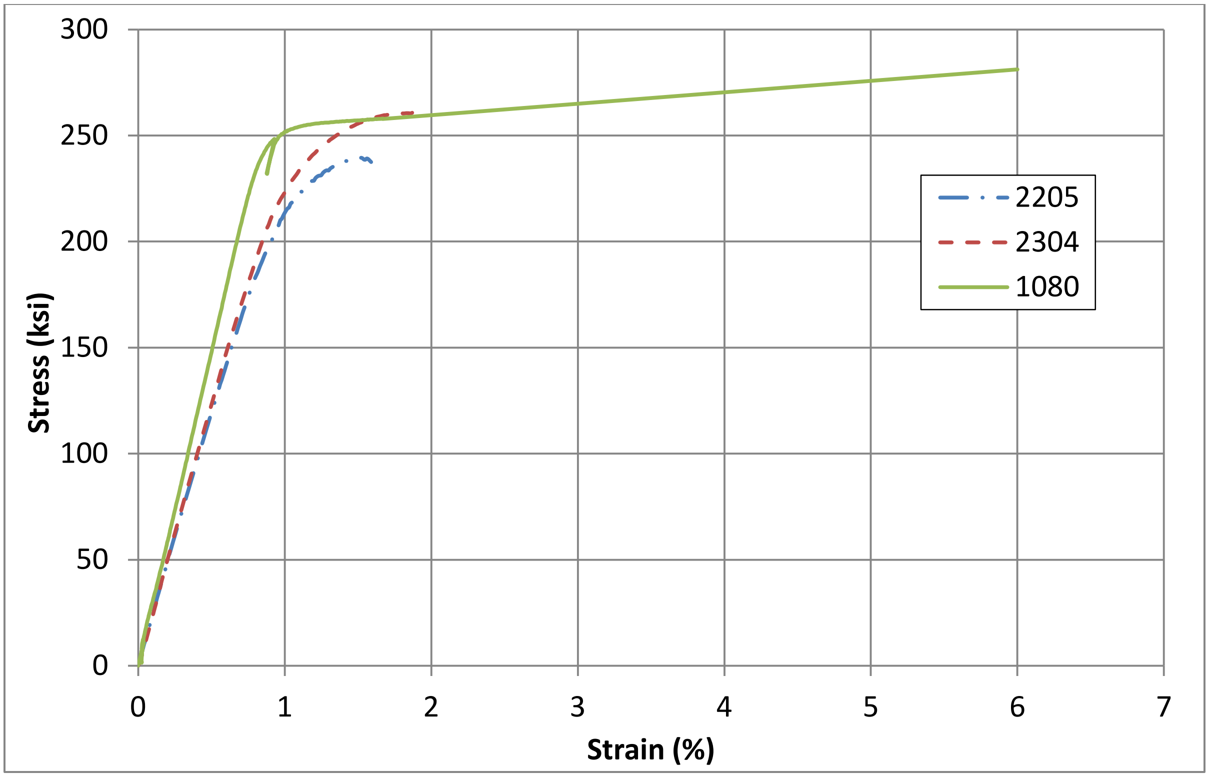


Fig. 4: Stress-Strain Curves of Strand Specimens

Table 2: Mechanical Properties of Strand Specimens

Alloy	f_y -0.2% Offset (ksi)	f_y -1% Strain (ksi)	UTS (ksi)	Ultimate Strain (%)	E (ksi)
1080	254.7	251.5	281.8	5.89	29400
2205	228.7	215.0	241.5	1.60	23500
2304	242.0	223.5	260.5	1.87	24100

STRESS RELAXATION OF HSSS STRAND

Figure 5 shows the stress relaxation of both HSSS alloys at differing initial stresses, and their 1000 hour losses are summarized in Table 3. These losses were extrapolated from the 200 hour tests using logarithmic regression. Though there is variation due to cyclic temperature fluctuation in the room, the data adheres well to logarithmic trend.

Three 1000 hr tests at 70 % UTS initial stresses revealed an average loss of 2.49 % for 2205 strand, slightly less than the limit set by ASTM A416 for low relaxation prestressing strand. At an initial stress of 80 % UTS, relaxation also satisfied ASTM A416, but also exhibited less relaxation loss than the tests conducted at 70 % UTS. More tests are necessary to verify these data, as it is unexpected that less relaxation would occur when higher initial stress is applied.

When attempting to load 2304 strand to an initial stress of 70 % UTS, one of the outer wires failed prior to this target stress. After unloading the specimen, it was concluded that the failure was caused by the teeth of the chuck grip which formed stress concentrating notches. Further tensile testing utilizing chucks as grips was conducted to determine the extent of the notch sensitivity of the 2304 strand and showed that the stress at which this failure occurs was approximately 161 ksi equal to 62 % UTS. Since the chucks used in testing are similar to the ones used in prestressing operations, it was assumed that a maximum allowable stress of 40 % UTS would need to be implemented in practice, and relaxation testing was conducted at this initial stress level.

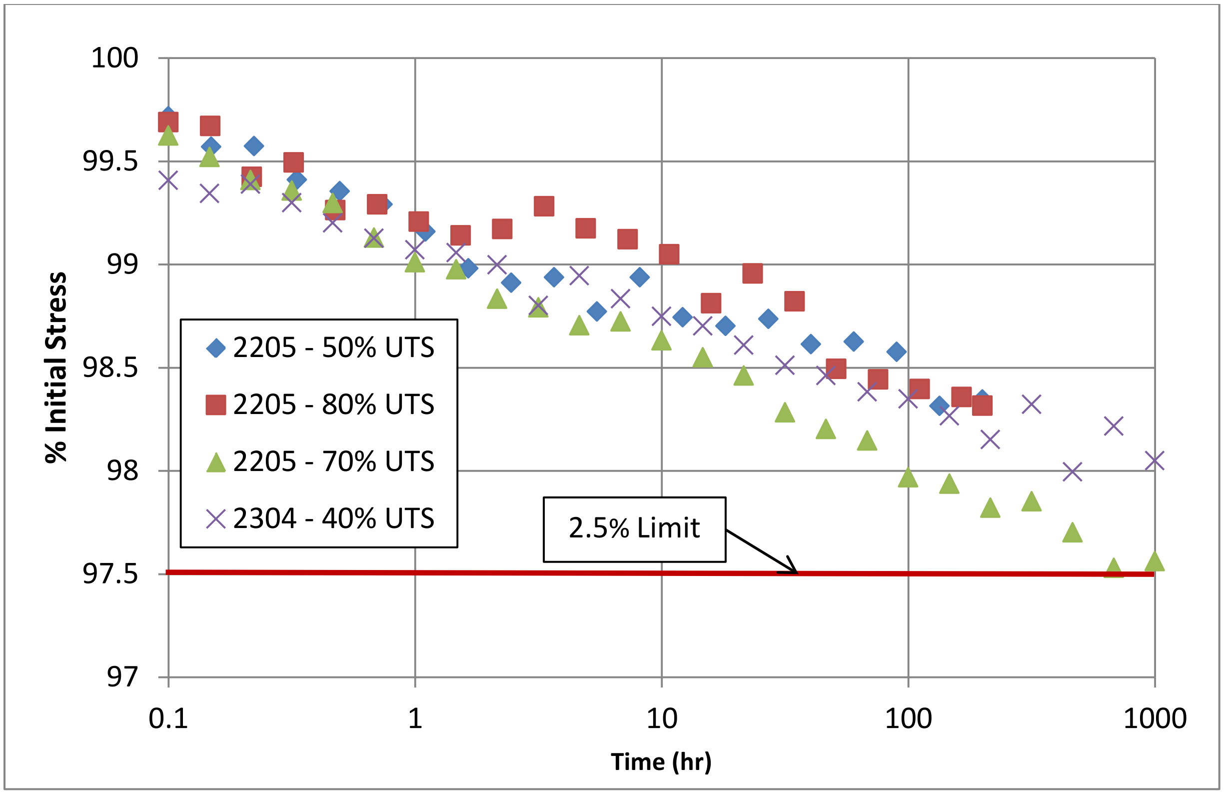


Fig. 5: Stress Relaxation of Strand Specimens

Table 3: Stress Relaxation Losses at 1000 Hours

Test	1000 HR Stress (% Initial)	% Loss	Lo-Lax Limit
2205 - 70% UTS 1000 HR	97.51	2.49	<2.5 %
2205 - 50% UTS 200 HR	97.99	2.01	-
2205 - 80% UTS 200 HR	98.09	1.91	<3.5 %
2304 - 40% UTS 1000 HR	97.93	2.07	-

STRESS-STRAIN BEHAVIOR OF DRAWN WIRES

Figures 6 and 7 show the stress vs. strain behavior of drawn wire samples taken from varying points in the manufacture of the HSSS strand. Tables 4 and 5 detail the mechanical properties calculated from these curves along with the reduction of area (RA) from drawing. The designation for each wire refers to the die from which the sample was taken. There are two samples from the #7 die—one taken directly after drawing (UW) and another taken from the center wire of the heat treated strand (HW).

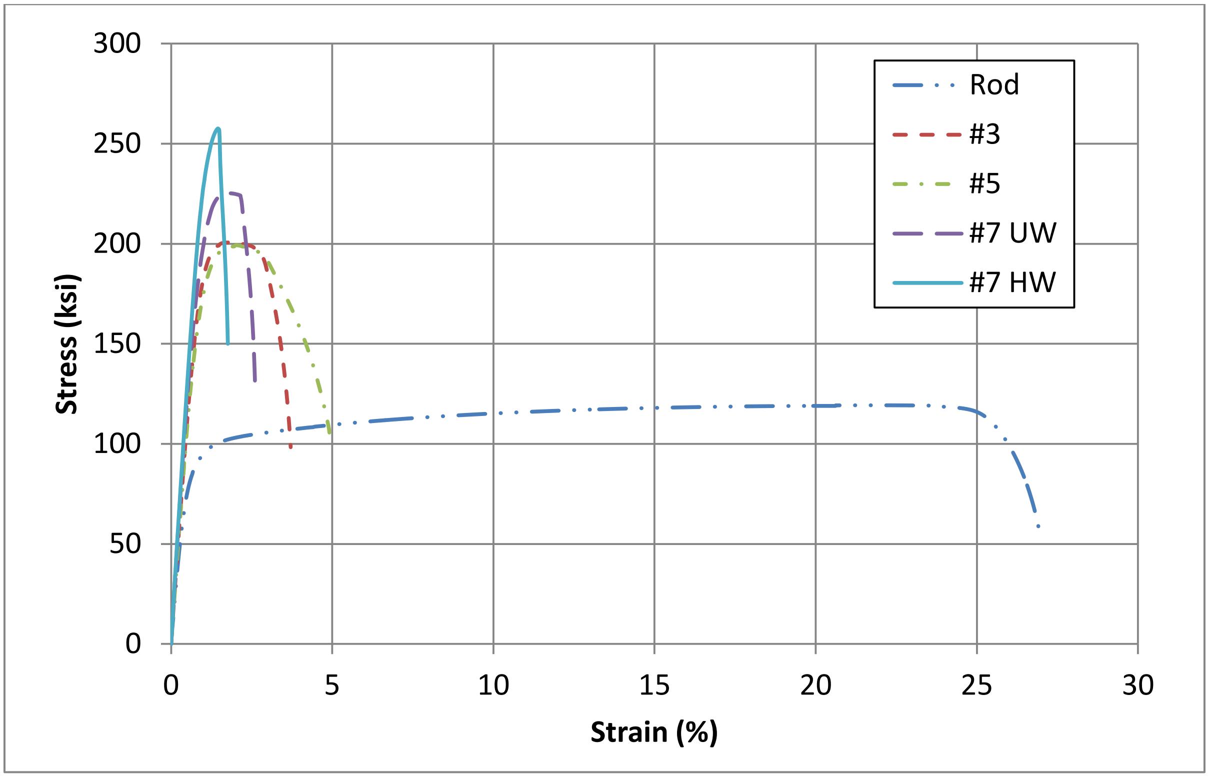


Fig. 6: Stress-Strain Curves of 2205 Wire Samples

Table 4: Mechanical Properties of 2205 Wire Samples

Material	RA (%)	f_y (ksi)	UTS (ksi)	Ultimate Strain (%)	E (ksi)
Wire Rod	0	85.5	119.1	26.9	18400
#3	55.6	185.0	201.0	3.71	22200
#5*	69.5	175.6	199.3	4.91	21700
#7 UW	78.7	207.3	225.2	2.62	24100
#7 HW	-	244.2	258.0	1.76	25500

*Due to limited materials, a shorter segment was tested in a different testing machine. Increased ultimate strain is likely caused by the magnification of strain localization caused by the smaller gage length. Other variability is likely due to the machine used.

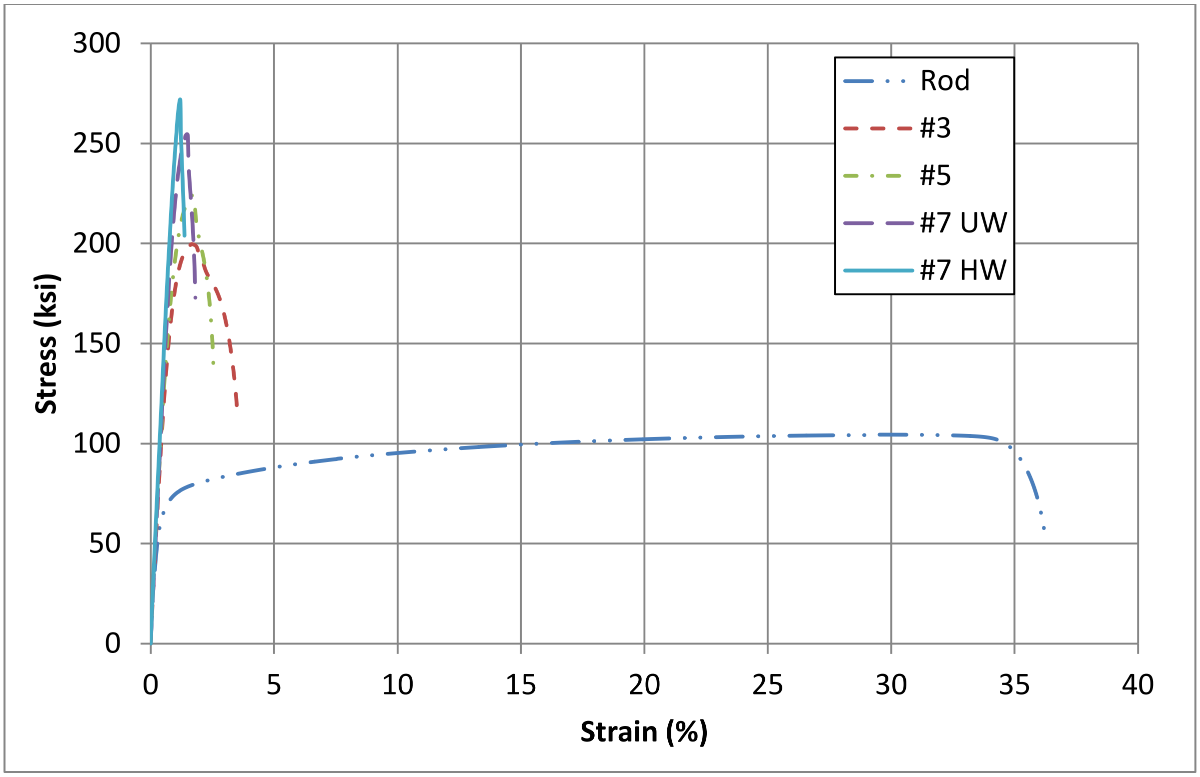


Fig. 7: Stress-Strain Curves of 2304 Wire Samples

Table 5: Mechanical Properties of 2304 Wire Samples

Material	RA (%)	f_y (ksi)	UTS (ksi)	Ultimate Strain (%)	E (ksi)
Wire Rod	0	67.3	104.3	36.22	18100
#3	54.6	176.7	199.7	3.51	22600
#5	68.9	198.9	224.0	2.54	23000
#7 UW	78.3	238.3	254.7	1.81	25200
#7 HW	-	263.4	271.8	1.38	25600

Reduction of area by cold drawing led to clear increases in yield stress, UTS, and Young's modulus, but significant decreases in ultimate strain in both stainless steels. While wire rods showed high ultimate strain (above 25%), none of the drawn samples exhibited significant post-yield plasticity or strain hardening, and necking occurred short after yield. Of the two materials, 2304 gained strength more effectively with reduction of area. This is potentially due to the formation of strain-induced martensite in the austenite fraction.

Thermomechanical treatment led to significant increases in UTS and further decreases in ductility. These effects can be accounted for by a decrease in residual stresses caused by the treatment. During drawing, high compressive residual stresses are unevenly induced along the length of the wire. These areas of high residual stress yield before areas of low residual stress. Therefore, after treatment which reduces residual stresses and provides a more uniform distribution, an increase in UTS is observed. In the untreated wire, more strain is required to overcome residual compressive strains. Therefore, a higher ultimate strain is observed prior to treatment. However, these ultimate strains are based on the magnification of strain localization due to the gage length. At larger scales, ultimate strains would be reduced to approximately the yield strain since there is little ductility in any of the drawn wires after this point.

CONCLUSIONS

Seven wire ½" strand was produced from duplex grade 2205 and 2304 stainless steel using practices and machinery in place for current strand production using 1080 steel. The stainless steels were selected based on preliminary testing of their corrosion resistance, mechanical and stress relaxation properties, availability and cost. Experimental studies were performed on the strand to determine mechanical properties and stress relaxation losses, and further testing on wire specimens was performed to show the effects of cold drawing and heat treatment. Conclusions from this study include:

- 2205 and 2304 duplex stainless steels can both be used to create strands that achieve strengths comparable to strand currently in practice.
- Due to lower Young's modulus in the HSSS strands, estimating the yield strength at 1 % strain provides a value 5 to 8 % lower than the yield strength obtained using the 0.2 % offset method. A better approximation of yield strength can be obtained by taking the stress at 1.2 % strain or by using the 0.2 % offset method.
- Ultimate strain of the stainless steels is greatly diminished with reduction of area by cold drawing. Yielding of the strand was immediately followed by necking failure, and no general plastic deformation or strain hardening throughout the specimen was observed. Ultimate strain of the stainless steel strands was found to be approximately 30 % of the ultimate strain of 1080 strand.
- 2304 strand failed due to notch sensitivity at 62% UTS when gripped by standard chucks, and as a result may only be effectively stressed to around 40 % UTS in practice.
- The 2205 strand investigated provides low relaxation prestressing strand, i.e. less than 2.5 % relaxation loss at 1000 hr when initially stressed to 70 % UTS and less than 3.5 % loss at 1000 hr when initially stressed to 80 % UTS. The 2304 strand could not be stressed to these levels, but underwent approximately 2.1 % loss over 1000 hr when initially stressed to 40 % UTS.

Overall, the 2205 HSSS strand showed excellent promise for use in prestressed concrete structures subjected to high corrosion environment. The notch sensitivity in 2304 strand indicated that it could not be used effectively in practice. Additional research is necessary to improve mechanical behavior of the HSSS strands, specifically increasing the ultimate strain and ductility of the HSSS strand. Furthermore, studies into the performance of HSSS strand in concrete and the influence of changes in mechanical properties are required prior to implementation of HSSS strand in PSC structures.

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